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EFFICIENCY OPTIMIZATION IN A RAINBOW QUANTUM DOT SOLAR CELL

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Abstract- In this paper, we have calculated the efficiency and I-V characteristic of a Quantum Dot (QD) Solar Cell (SC) based on multi-stacked different-sized InGaN QDs on GaN substrate. In order to engineering the confinement states of QDs, we have inserted different-sized QDs in i-region of a p-i-n structure which includes different layers. This leads to Rainbow SCs.

Keywords: QD Solar Cells, InGaN QDs, Energy Conversion Efficiency.

I. INTRODUCTION

Direct wide band gap group III-nitrides semiconductor materials, including GaN, AlGaN and InGaN can cover a spectral range from ultra violet to infrared, with high mobility, high peak and saturation velocities, high absorption and radiation coefficients. These properties make them unique and very suitable for modern electronic and optoelectronic applications such as blue semiconductor laser, light emitting diodes, sensors and photodetector [1-3]. Also, these materials got useful for the photovoltaic applications by intermediate-band solar cells [4].

Here, by inserting quantum dots (QDs), it is illustrated that solar cell's (SC) efficiency can be improved [5]. Theoretical models predict maximum solar energy conversation up to 63% by this type of SC [6]. Recently, several experimental results reported for multi-stacked QDs in the intrinsic region of typical p-i-n structure SCs [7-9].

The band gap of $In_xGa_{1-x}N$ can be varied to make an overlap with solar spectrum (0.5-3.5 eV) [11], and $In_xGa_{1-x}N$ has a good lattice match with GaN for all fractions of in [12], thus we had proposed a multi-stacked structure of different-sized InGaN QDs (M=20 layers) in i-region of p-i-n SC structure. We can design ideal band gaps for maximum solar conversion efficiency or "rainbow" SC. In this work, we had inserted 20 layers of InGaN QDs with sizes between 6 nm and 14 nm in i-region of GaN p-i-n SC, and in order to intercept intermediate band broadening, we have used same sized QDs in a layer. To achieve this condition we should control the size of QDs precisely. We calculate the photocurrent density and efficiency of SC for each layer and I-V curves in one 1.5 AM condition. Our calculation has shown the short-circuit current (j_{sc}) and the open-circuit voltage (V_{oc}) can be independently optimized because the absorption edge and spectral characteristics can be modified by the size and In fraction of the InGaN QDs. It is possible to achieve a high density QD active layer of p-i-n SCs which provides an intermediate band for efficient photovoltaic effects.

II. BACKGROUND THEORY

The illustrated theoretical model used in the present work with 20 multi-stacked layers of different-sized InGaN QDs in i-region of a p-i-n SC. Figure 1 shows the proposed p-i-n SC. Sandwiched i-region between acceptor and donor regions of GaN consists $In_xGa_{1-x}N$ QD's layers. Each layer has same sized QDs to support only one confined state for electrons in each layer. Different-sized QDs in different layers of SC efficiently overlap the large part of the sunlight spectra, so by this means Rainbow SCs can be designed.

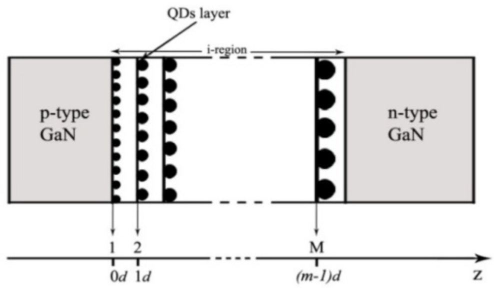


Figure 1. The structure of p-i-n quantum dot SC with different-sized QDs in different layers

The processes of photon absorption, carrier relaxation and recombination can be distinguished by the Shockley-Hall-Read, and the following rates for the Mth layer's of QDs are presented as corresponding to Figure 2;

(1) Electron capture by QDs:

$$C_m = \alpha\, n(z,m)\, N_s (1 - f_n^m) \quad (1)$$

(2) Electron escapes from QDs:

$$E_m = \beta\, N_s f_n^m \quad (2)$$

(3) Recombination in QDs:

$$R_m = \gamma\, N_s (f_n^m - f_{n0}) \quad (3)$$

(4) Optical generation in QDs:

$$g_m = \kappa\, N_s (1 - f_n^m) \quad (4)$$

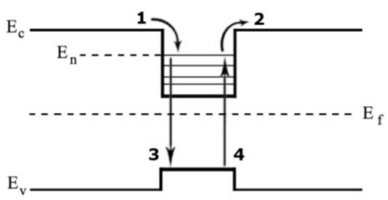


Figure 2. Mind processes happen in QDs

The rates of the above mentioned processes (per unit area and per unit time) depend on the QD density and QDs layer position within i-region. α, β, γ and κ are the capture, escape, recombination and generation coefficients, respectively. In the steady state the following electrical charge continuity equation should be valid,

$$(C_m - E_m) + (R_m - g_m) = 0 \quad (5)$$

By solving the following equation, we have calculated U_T^m, U_s^m and U_{tot}^m which are the effective surface recombination rate, effective transition rate and the total recombination rate for Mth QD's layer.

The total generated photocurrent in i-region by taking into account the existence of QDs through the total effective recombination rates (U_{tot}^m) can be calculated self-consistently by solving the current continuity equation for inter-layer regions.

Assuming the drift component of current as the main current and neglecting the recombination in the inter-layer regions, for the free electron density $n(z,m)$ in the inter-layer region we get:

$$-\mu_n E \frac{dn(z,m)}{dz} = F(\lambda)\alpha(\lambda)\exp[-\alpha(\lambda)z] \quad (6)$$

where μ_n, E, n(z,m), $F(\lambda)$ and $\alpha(\lambda)$, are the electron mobility of barrier region, electric field, free electron density in the inter-dot region and light absorption coefficient, respectively.

By solving Equation (6) the free electron density in the first interval layer $0 \le z \le d$ is obtained. We can find the photocurrent density generated in the first inter-dot region especially at the layers interface ($z=d$). Consequently, for the remained layers we obtain,

$$q\frac{2D_n}{L_n} n(z,m) = j_n^{m-1} - qU_{tot}^m \quad (7)$$

The total collected photocurrent density at the end of Mth layer (as the last layer) from the intrinsic region, include photocurrents density generated in both inter-dot regions and QDs layers is formulated as:

$$j_n^m = j_{nQD}^m + qF(\lambda)(1 - \exp(-\alpha(\lambda)d) \quad (8)$$

where q, $F(\lambda)$, $\alpha(\lambda)$ and d are the electrical charge, Flux of incident light with wavelength λ, light absorption coefficient, and a QDs layer thick, respectively. The first term of Equation (8) is the contribution of QDs layers and the second term is created by inter-dot regions. Short circuit photocurrent for a p-i-n structure is given by,

$$j_{sc} = f_i\, (j_n^p + j_p^n + j_n^m) \quad (9)$$

where $j^p{}_n$ and $j^n{}_p$ are total photocurrent collected by p type and n type, respectively. f_i is the transport factor which represents the mean probability of an electron or hole crossing the i-region without capturing and recombination ($f_i = 0.12$). Furthermore, we assumed that the effective diffusion-drift length of carriers to be larger than i-layer width. In this paper, we have calculated only the generated photocurrent in i-region and neglected the generated currents in p and n-regions, so we neglect $j^p{}_n$ and $j^n{}_p$,

$$j_{sc} = f_i\, j_n^m \quad (10)$$

Using the standard superposition model of solar cell, the current density can be presented by,

$$j = j_{sc} - j_0[\exp(eV/kT) - 1] \quad (11)$$

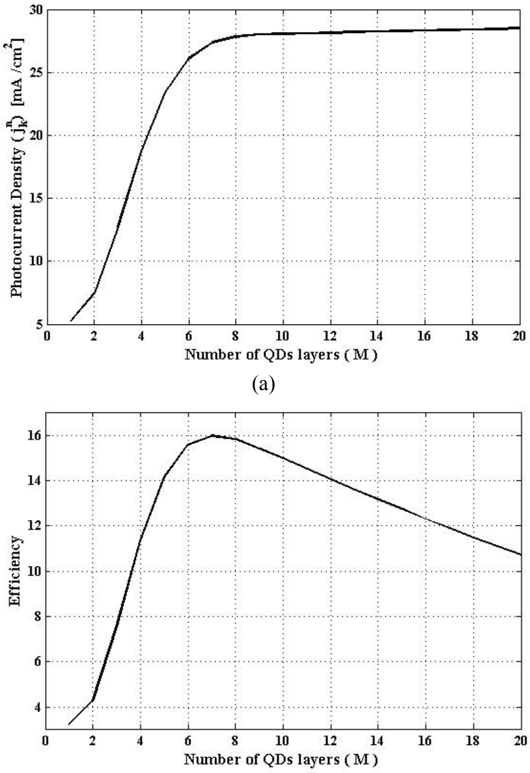
where j_0 is the reverse saturation current of the junction which is contribution of minority carriers that generated at the depletion layer edges (j_{s1}) and in i-region (j_{s2}) due to thermal excitation. Solar cell's power conversion efficiency at the maximum power point can be calculated by,

$$\eta = \frac{V_m J_m}{P_0} = \frac{kT}{e}\tau_m[j_{sc} - j_0(e^{\tau_m} - 1)]/p_0 \quad (12)$$

where P_0=116 mW/cm^2 is the incident solar flux for 1 sun 1.5 AM condition and τ_m is the optimum time constant.

III. SIMULATION RESULTS

The results of the Photocurrent density and efficiency as a function of the number of QD layers in i-region (M) and for two different lifetimes (τ_r=1 and 100 ps) are illustrated by Figures 4 and 5. Figure 4 shows the total photocurrent density (j) and efficiency (η) curves versus the number of QDs layers for τ_r=1 ps.



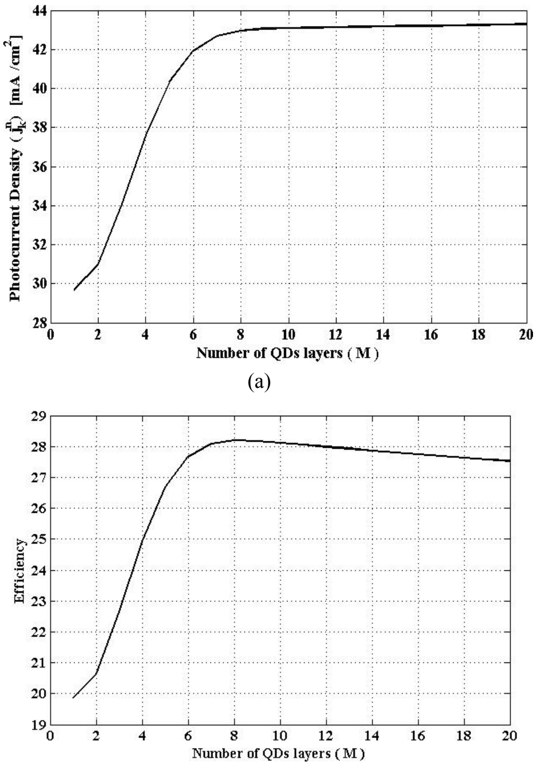
(a)

(b)

Figure 4. (a) Total photocurrent density and (b) efficiency versus the number of layers (M), for τ_r=1 ps

The increasing slope of current density becomes sharp for layers 1 to 7 and the efficiency reaches to the maximum value (16%). If the number of layers increases from 8 to 20 the slope of current density slowdowns and the efficiency falls down. In this case, we have obtained j_{sc}= 28.49 mA/cm^2, V_{oc}= 0.707 V and η_{max}= 16% in for the purposed SC scheme. Thus we can conclude that 7 layers of QDs is optimal case to achieve maximum efficiency.

Figure 5 illustrates the total photocurrent density (j) and efficiency (η) of the proposed SC versus the number of QDs layers for τ_r=100 ps. The increasing slope of current density becomes sharp from layers 1 to 8. If the number of layers increases to more than 8 layers the slope of current density slowdowns. Because, carrier's concentration around the adjacent layers of p region increases, so the QDs of these layers cannot play as generation center. Thus, we can conclude that 8 layers of QDs is optimal case to achieve maximum efficiency. We calculated j_{sc}= 43.3 mA/cm^2, V_{oc}= 0.718 V and η_{max}=28.3% for eight layers, while without QDs we obtained j_{sc}= 32.05 mA/cm^2, V_{oc}= 0.637 V and η= 16.1%. In fact, by using QDs in i-region we can enhance short-circuit current (j_{sc}) which results in significantly enhanced energy conversion efficiency.



(a)

(b)

Figure 5. (a) Total photocurrent density and (b) efficiency versus the number of layers (M), for τ_r = 100 ps.

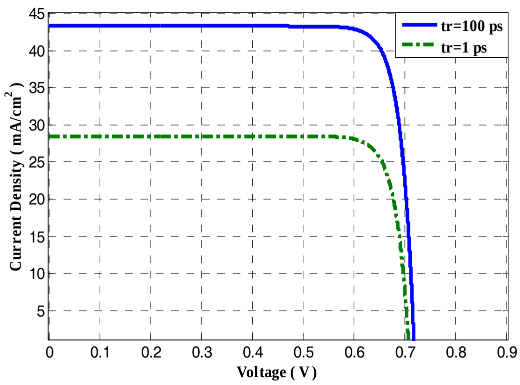


Figure 6. The generated current density of *Sc* versus the produced voltage (I-V characteristic)

I-V characteristic of the multilayer QD inserted in i-region of p-i-n solar cell is illustrated by Figure 6, Where, the green colored dashed-dot curve denotes to the rapid carrier recombination of QDs (τ_r=1 ps) and blue colored solid curve is related to the slow carrier recombination of QDs (τ_r=100 ps). We know that for the case of rapid carrier recombination of QDs, the major number of carriers can't reach to the electrodes while for slow carrier recombination case approximately all of the carriers can reach to the electrodes. Thus, for the latter case generated current Density increases and resulted in efficiency enhancement.

IV. CONCLUSIONS

In this paper, we have presented a modified case for performance enhancement of multilayer QD inserted in *i*-region of p-i-n solar cell. We have calculated the generated current density of the proposed SC for two lifetime values. One of the cases have calculated for rapid carrier recombination (τ_r=1 ps) and the other one is for slow carrier recombination (τ_r=100 ps). In the latter case the generated carriers have sufficient opportunity to escape out from the QDs and reach to the electrodes, so this results in a high current density. To transmit the most of carriers to electrodes, we have to limit the intrinsic region length of the SC. Also, we have concluded the best numbers of the QDs layers to enhance the maximum energy conversion efficiency.

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BIOGRAPHY

Ali Rostami received his Ph.D. degree in photonic/electronic engineering from Amirkabir University of Technology, Tehran, Iran in 1998. He was in sabbatical leave in the University of Toronto, Canada in 2004-2005 at the Photonic Group. He is currently full Professor of Electronic Engineering and Photonics Science at the University of Tabriz, Tabriz, Iran. His teaching and research interests include optical integrated circuits and optoelectronic devices. He is a member of the Optical Society of America. He is the author and co-author of more than 250 scientific international journals and conference papers and 10 text books in Farsi, 2 books in Springer publisher and 4 book chapters in international publishers. Also, he collaborates with some international journals as reviewer boards and works as editorial committee of two Iranian and one international journal. He has served on several other committees and panels in government, industry, and technical conferences. Also, he is founder of Photonics and Nanocrystals Research Lab. (PNRL) at University of Tabriz. School of Engineering-Emerging Technologies is another project that is established by him at University of Tabriz since 2008. Also, he is chair of center of Excellence for mechatronics since 2005. He was selected as distinguished researcher of the University of Tabriz several times and in 2007 he was elected as distinguished researcher in engineering field by Ministry of Science, Research and Technology in Iran. He currently is vice chancellor for research and technology at University of Tabriz since 2008.